The Chemical Residue of a
White Dwarf-Dominated Galactic Halo

Brad K. Gibson & Jeremy R. Mould

Mount Stromlo & Siding Spring Observatories,
Institute of Advanced Studies,
Australian National University,
Weston Creek P.O., Weston, ACT, Australia 2611

ABSTRACT

Halo initial mass functions (IMFs), heavily-biased toward white dwarf (WD) precursors (i.e. $\sim 1 \rightarrow 8$ M$_\odot$), have been suggested as a suitable mechanism for explaining microlensing statistics along the line of sight to the LMC. Such IMFs can apparently be invoked without violating the observed present-day WD luminosity function. By employing a simple chemical evolution argument, we demonstrate that reconciling the observed halo Population II dwarf abundances (i.e. [C,N/O]≈ -0.5), with that expected from the postulated "WD-heavy" IMF (i.e. [C,N/O]$\gtrsim +0.5$), is difficult.

Subject headings: stars: luminosity function, mass function — Galaxy: abundances — Galaxy: halo — dark matter

arXiv:astro-ph/9612133v1 13 Dec 1996

1. Introduction

Analysis of the first year's MACHO (Alcock et al. 1993) data led some to conclude that low-mass stars and brown dwarfs could be responsible for the microlensing events seen along the line-of-sight to the Large Magellanic Cloud (e.g. Fujimoto et al. 1995; Méra, Chabrier & Schaeffer 1996). Reconsideration of this position seems apparent in light of the release of the second year's worth of MACHO data (Alcock et al. 1997) which points to substantially higher-mass "lenses".

A dark baryonic halo comprised primarily of white dwarfs (WDs) has been considered in this context on more than one occasion in the past. Adopting a variant of Larson's (1986) Galactic, bimodal, initial mass function (IMF), Hegyi & Olive (1986) clearly demonstrated that such a scenario was untenable, for IMFs with lower-mass cutoffs of 2 $M_\odot$, based simply upon an overall overproduction of heavy elements. Unlike Hegyi & Olive (1986), who adopted an upper-mass limit of 100 $M_\odot$, Ryu et al. (1990) considered truncating this limit at progressively smaller values, until metal overproduction was minimized, concluding finally that only very specific, and limited, ranges were allowed. Further arguments against WD-dominated halos came from Charlot & Silk's (1995) examination of their high-redshift photometric signatures. Charlot & Silk found that halos whose WD mass fraction was $\gtrsim 10\%$ would clearly violate the galaxy number counts.

Recently, Adams & Laughlin (1996), Chabrier, Segretain & Méra (1996), and Fields, Mathews & Schramm (1996), have explored the ramifications of a WD precursor-dominated halo IMF, ensuring that each of their respective favored models did not lead to inconsistencies with the observed present-day halo WD luminosity function. The *detailed* nucleosynthesis implications were beyond the scope of these initial studies (e.g. global metallicity Z was cursorily considered, but the evolution of specific elements was not). Our follow-up work, described herein, is a first step in redressing this omission; it is not meant to be exhaustive, but does serve to indicate potential problems with the WD precursor-dominated IMF scenario, not fully appreciated in these analyses.

In Section 2, we briefly describe the chemical evolution code adopted. We then concentrate on the early interstellar medium (ISM) evolution of carbon, nitrogen, and oxygen, contrasting the implied behav-ior as a function of adopted IMF with observations of metal-poor halo dwarfs. Finally, qualitative arguments based purely upon the implied mass of ejected gas from the WD-precursor dominated IMF is presented. Our results are summarized in Section 3.

2. Analysis

2.1. Background

We adopt Gibson's (1996a,b) chemical evolution package, in order to follow the temporal history of CNO abundances in our simple Galactic halo model. The star formation rate is presumed to be proportional to the available gas mass, with a constant of proportionality (i.e. the astration parameter) $\nu = 10$ Gyr^{-1}. Such a formalism corresponds to an exponential star formation rate of the form $\psi \propto e^{-t/\tau}$, with $\tau \approx 0.11$ Gyr for $t \lesssim 0.4$ Gyr, and $\tau \approx 2.56$ Gyr for $t \gtrsim 0.4$ Gyr. Parallel calculations were made with higher and lower values for ν and τ, to ensure that our conclusions were not dependent upon these template values (which they were not).

We have not considered the role played by Type Ia supernovae (SNe) in what follows, as we will be primarily concerned with the CNO abundances, none of which are supplied by Type Ia's in any important quantity. Where this could be important though would be in the calculation of the present-day Type Ia SNe rate (and its accompanying increase in the mass of iron made available for subsequent generations of star formation). For example, the favored Chabrier et al. (1996) IMF discussed explicitly in the following subsection has a factor of two more mass tied up in the $3 \rightarrow 16$ $M_\odot$ regime, a range generally accepted as the progenitor mass range for most Type Ia binary-progenitors, regardless of whether mass transfer or WD-merging is the dominant mechanism (Greggio & Renzini 1983; Tornambè 1989).

The key ingredients in our modeling, as shall be elucidated upon in the following subsections, will be the adopted IMF and stellar yields. Before commenting upon their significance, let us first list briefly the fundamental observational constraints that we shall be concerned with in this paper. The observational datasets collated by Timmes et al. (1995) show that [C/O] in the halo dwarfs ranges from -1.2 to +0.3 dex for [Fe/H]$\lesssim$-1.5 [1]; [N/O], in the same metallicity

---

[1]On the other hand, Gratton & Caretta (1996) claim that the range of [C/O] in halo dwarfs is actually considerably smaller

regime, goes from -1.7 to +0.7 dex. [2] *The mean observed value for both ratios is [C/O]≈[N/O]≈ −0.5, with the majority (∼ 80%) of dwarfs lying within ±0.3 dex of the mean.* It is important to echo Timmes et al.'s remarks, and note that field and halo giants are simply not reliable indicators of any *ab initio* abundance pattern, as mixing processes along the giant branch can dramatically alter both carbon and nitrogen.

2.2. Initial Mass Functions

For brevity, we shall restrict our analysis to two different IMF forms – – the aforementioned favored WD precursor-dominated IMF of Chabrier et al. (1996),[3] which in turn will be contrasted against that of the canonical Salpeter (1955) IMF. Both are illustrated in Figure 1, normalized to unity over the mass range $0.1 \rightarrow 40.0$ M$_\odot$, clearly demonstrating, better than any words can, exactly how these two IMFs differ. It is apparent that Chabrier et al.'s IMF has effectively no component of sub-solar mass stars, while Salpeter's has almost 2/3 of the mass locked-up below 1 M$_\odot$. At the high mass end, Salpeter's IMF has $\sim 25\times$ as much mass locked into Type II SNe progenitors (i.e. $m \gtrsim 11$ M$_\odot$).

Not surprisingly, the Chabrier et al. (1996) IMF, because of its resultant dominance by WDs[4], is far more successful at replicating the inferred present-day Galactic halo mass-to-light ratio $M/L \gtrsim 100$ (e.g. Freeman 1996, and references therein), in the absence of a large non-baryonic component, than that of Salpeter's (1955). Adopting the isochrones of Bertelli et al. (1994), and following the photometric evolution prescription of Gibson (1996a), we found that for the models to be discussed later in this section (and Figure 4) $M_h/L_{\rm V} \approx 300$ (Chabrier et al. IMF) and $M_h/L_{\rm V} \approx 6$ (Salpeter IMF).

---

than this – i.e. [C/O]≈ −0.6 → −0.2, for [Fe/H] down to ∼ −2.0 – a fact which lends even further credence to the conclusions which follow.

[2] The halo dwarf [C,N/O] ratios were estimated from Timmes et al.'s (1995) Figures 11, 13, and 14, using the relation [C,N/O]≡[C,N/Fe]-[O/Fe].

[3] We could just as easily have chosen to use the Adams & Laughlin (1996) or Fields et al. (1996) IMF formalism, but their similarity to that of Chabrier et al.'s (1996) means that our conclusions are *not* dependent upon this choice.

[4] ∼ 50% of the present-day dynamical mass of the halo ($M_h \approx 10^{12}$ M$_\odot$ – Freeman 1996) is assumed to be locked into WDs, for the Chabrier et al. (1996) IMF under consideration here.
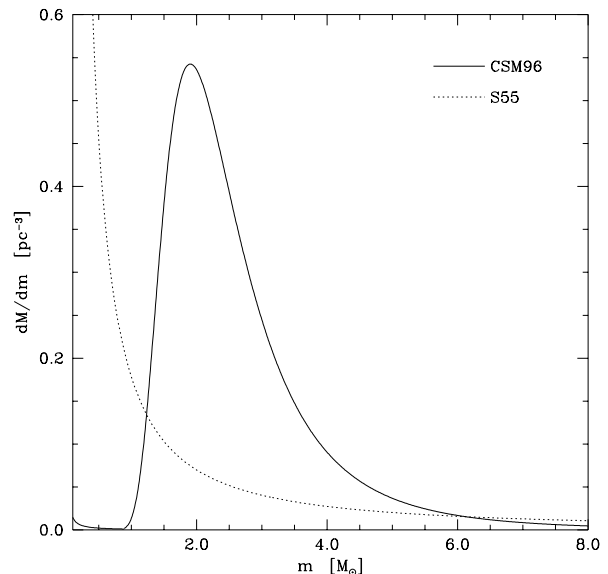

Fig. 1.— Comparison of the canonical Salpeter (1955) IMF (dotted curve), normalized to unity over the range $0.1 \leq m \leq 40.0$ M⊙, with the WD precursor-dominated IMF proposed by Chabrier et al. (1996) (solid curve).

2.3. Stellar Yields

Besides the IMF selection, the other key ingredient to our modeling is the adopted nucleosynthetic yields. We have chosen Woosley & Weaver's (1995) metallicity-dependent yields for Type II SNe ejecta,[5] although this is a relatively inconsequential decision as Type II SNe play a fairly unimportant role when coupled with the Chabrier et al. (1996) IMF. For the lower-mass asymptotic giant branch (AGB) precursors, our default yield prescription is that due to van den Hoek & Groenewegen (1996). We have considered competing prescriptions (i.e. Marigo et al. 1996 and Renzini & Voli 1981), a point to which we return to briefly, below, but stress that our conclusions are

---

[5] The published Woosley & Weaver (1995) Type II SNe models do not produce any primary nitrogen. Nitrogen yields, though, can be a strong function of the arbitrary prescription chosen for convective overshooting (Arnett 1996); Models kindly provided by F. Timmes, based upon the same code used by Woosley & Weaver (1995) but with an enhanced overshooting prescription (although one not at odds with observation), show that primary nitrogen was produced in their models with $m \geq 30$ M$_\odot$, but *only* for metallicities Z$\lesssim 0.01$. This massive star component of primary nitrogen has been used in lieu of the published values.
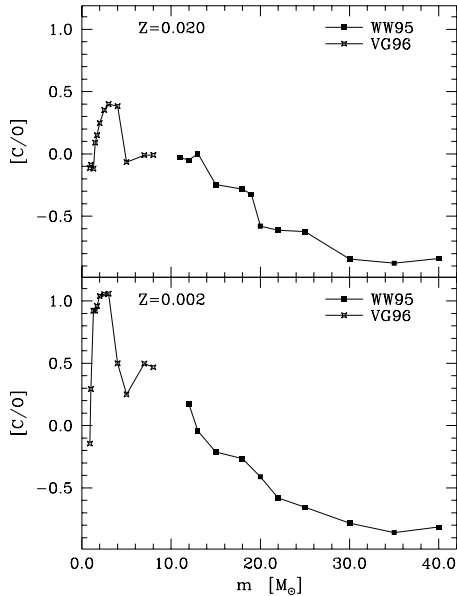
not dependent upon the AGB yields selected.

Fig. 2.— Ratio of ejecta carbon to oxygen predicted by the Type II SNe models of Woosley & Weaver's (1995) ([Fe/H]=-1.0, $m \gtrsim 10$ M$_\odot$), contrasted with low- and intermediate-mass AGB models of van den Hoek & Groenewegen (1996). Two different metallicities (solar – upper panel; 1/10 solar – lower panel) are highlighted. Recall that the halo dwarfs show the abundance pattern [C/O]≈[N/O]≈-0.5, albeit with large scatter.

Figure 2 illustrates the stellar ejecta's carbon-to-oxygen ratio, as a function of initial mass m, for stars of solar metallicity (top panel), and one tenth solar metallicity (bottom panel). Even a cursory inspection of Figure 2 allows one to anticipate problems that will arise in reconciling *any* intermediate-mass-biased IMF, with the average halo dwarf observations of [C,N/O]≈ -0.5 – specifically, the *only* portion of the IMF which could possibly leave the imprint of such a carbon underabundance relative to oxygen in the halo dwarfs comes from $m \gtrsim 15$ M$_\odot$. In particular, any IMF which is predicated upon being heavily biased toward WD precursors (i.e. $m \approx 1 \rightarrow 5$ M$_\odot$) cannot help but *overproduce* carbon with respect to oxygen. This is demonstrated even more so in Figure 3 which shows a close-up of the mass region in question.

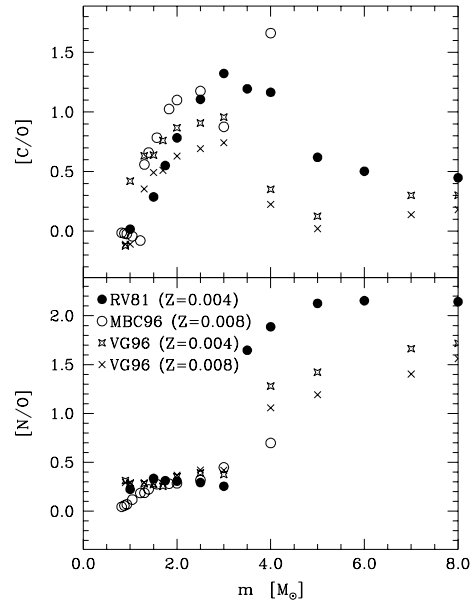Figure 3 shows examples of the low metallicity

Fig. 3.— Ratios of ejecta carbon and nitrogen to oxygen predicted by the sub-solar metallicity AGB models of Renzini & Voli (1981) and Marigo et al. (1996). Recall that the halo dwarfs show the abundance pattern [C/O]≈[N/O]≈-0.5, albeit with large scatter.

AGB yield predictions of van den Hoek & Groenewegen (1996), Marigo et al. (1996), and Renzini & Voli (1981), for both [C/O] and [N/O]. The first two references detail the differences in the models, but again though, for our purposes, whether we choose one compilation over the other in no way leads to sub-solar abundance ratios of carbon or nitrogen with respect to oxygen, regardless of how one arbitrarily distributes mass in the $m \lesssim 8$ M$_\odot$ regime.

An immediate caveat springs to mind at this point – our conclusions rest squarely upon the applicability of the relevant yield compilations. If the low-mass stellar evolution models upon which these compilations are based could be shown to be severely in error, then one could conceivably relax the argument of the previous paragraph. In this vein, Fujimoto et al. (1995) rightly note that the evolution of Z=0 intermediate-mass stars may be quite different from simply extrapolating the tabulated solar and mildly sub-solar metallicity models to arbitrarily low Z.[6] On the other hand, Fujimoto et al. claim that

---

[6]Specifically, we are forced to extrapolate the tabulated yields

extreme nitrogen-rich carbon stars should be the outcome of primordial composition evolution, which referring to the bottom panel of Figure 3 will only drive the expected [N/O] ejecta from this low-metallicity WD precursor-dominated IMF to values even further from the observed halo dwarf values of [N/O]≈ -0.5. Regardless, this entire extrapolation procedure is, at some level, a leap of faith, and we reserve the right to modify our conclusions once primordial metallicity AGB nucleosynthetic yields become available!

2.4. Results

The [C,N/O] evolution of our model halo ISM, under the input parameters outlined above, is illustrated in Figure 4. The solid curve represents the expected behavior utilizing the favored Chabrier et al. (1996) IMF, whereas the dotted curve is the corresponding result when implementing the Salpeter (1955) IMF. The observational constraints, from the compilation of Timmes et al. (1995), are indicated by the shaded regions. All of the ~ 150 halo dwarfs in Figures 13 and 14 of Timmes et al. lie within the bounds of the outer shaded region; $\sim 80\%$ of the sample lies within the inner region. The ISM metallicity at $\log t \approx 8.15$ is Z≈ 0.001; only a small halo stellar component exists at metallicities higher than this (Fields et al. 1996), which is why we have ended the shaded regions there.

A few general comments regarding the morphological behavior of the curves in Figure 4 can be made now – the turnoff-time for an 8 M$_\odot$ star is approximately $\log t = 7.56$ (Schaller et al. 1992), which corresponds to the point in the bottom panel at which [N/O] begins its initial dramatic increase, not surprisingly. The parallel increase in [C/O] is delayed somewhat relative to [N/O], until ~ 4 M$_\odot$ stars start turning off the main sequence (i.e. $\log t \approx 8.16$). Again, this could have been anticipated by referring back to the carbon and nitrogen behavior of Figure 3. The decline beyond $t \approx 0.3$ Gyr coincides with the expected dilution in [C,N/O] as stars with masses below ~ 2 M$_\odot$ start returning their ejecta to the ISM (recall Figure 3). The ISM [Fe/H] in Figure 4 attains the values -2.3, -2.0, -1.0, and +0.0, at $\log t =$7.78, 7.89, 8.27, and 9.31, respectively.

Fig. 4.— Evolution of the ISM [C/O] and [N/O] for the model described in Section 2. The two IMFs of Figure 1 are shown – Salpeter (dotted curve) and Chabrier et al. (solid curve). The Renzini & Voli (1981) yields for low- and intermediate-mass stars were assumed. The observational constraints, from Timmes et al. (1995), are indicated by the shaded regions. See text for details.

Figure 5 parallels that of Figure 4, but now shows how the chemical evolution depends upon the choice of AGB yields. The behavior in each case is qualitatively similar to that described in the previous paragraph, and indeed, could have been anticipated from Figure 3 – (i) [C/O] peaks several tenths in dex higher with the Marigo et al. (1996) yields, because of the very high [C/O] in their [Fe/H]=-0.40, $m = 4$ M$_\odot$ model. van den Hoek & Groenewegen's (1996) carbon and nitrogen yields are mildly reduced, in comparison with those of Renzini & Voli (1981) (see Figure 3, which results in their somewhat lower [C/O] in Figure 5. (ii) The [N/O] behavior, when using Marigo et al., is improved over that of the "competitors" (although, recall that its [C/O] behavior was worse), as inspection of the lower panel of Figure 3 intimates; Marigo et al. have no [N/O]$\gtrsim +1$ models for $m \gtrsim 3.5$ M$_\odot$ (enhanced convective overshooting being the primary cause). Such a difference leads to [N/O] ranging from $\sim +0.0$ to $\sim +1.0$, when using Marigo et al., as op-

---

to metallicities lower than [Fe/H]=-1.00, -0.40, and -0.70, for van den Hoek & Grownewegen (1996), Marigo et al. (1996), and Renzini & Voli (1981), respectively, to arbitrarily low halo metallicities. These values represent the minimum [Fe/H] considered in the respective models.
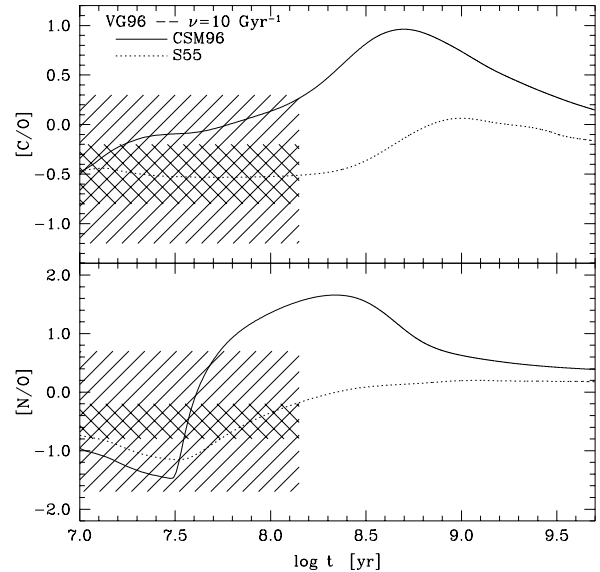
posed to the $\sim +0.0$ to $\sim +2.0$ we see in Figures 4 and 5, when using Renzini & Voli or van den Hoek & Groenewegen. We do not show the Salpeter (1955) curves in Figure 5 as they are very similar to that shown in Figure 4; the Salpeter IMF is relatively insensitive to the AGB yield selection. When using the van den Hoek & Groenewegen AGB models, all yields for times $\log t \lesssim 8.15$ were based upon extrapolating beyond their minimum Z model (i.e. Z=0.001); for the Marigo et al. models, the extrapolation "regime" was $\log t \lesssim 8.35$, and for Renzini & Voli, $\log t \lesssim 8.24$.
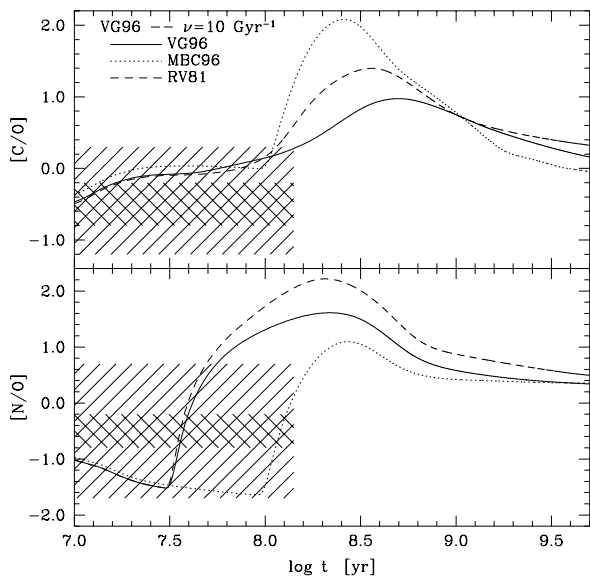

Fig. 5.— Evolution of the ISM [C/O] and [N/O] for the model described in Section 2. Three different low and intermediate-mass stellar yields are compared – Renzini & Voli (1981), Marigo et al. (1996), and van den Hoek & Groenewegen (1996). The Chabrier et al. (1996) IMF is adopted in all cases. The observational constraints, from Timmes et al. (1995), are indicated by the shaded regions. See text for details.

Recalling the observational constraint that Population II halo dwarfs have an intrinsic mean [C,N/O]$\approx$ -0.5, the conclusion to be inferred from the Chabrier et al. (1996) curves of Figure 4 is fairly obvious. *The combination of the WD precursor-dominated IMF, with the AGB yields of van den Hoek & Groenewegn (1996), leads to inevitable overproduction of carbon and nitrogen, relative to oxygen, by factors of $\sim 5 \rightarrow 30$ and $\sim 8 \rightarrow 60$, respectively, for all times $t \gtrsim 0.1$*

Gyr. We stress that the van den Hoek & Groenewegen yields are the most favorable compilation in this regard; adopting the Renzini & Voli or Marigo et al. yields only exacerbates the problem (by a *further* factor of $\lesssim 10$), especially the former, as far as nitrogen goes, and the latter, as far as carbon goes. On very short timescales, then, this enrichment of the halo ISM should be reflected in the present-day Population II halo dwarfs, [7] which, as was noted in Section 2.1, is simply not the case. The Salpeter (1955) IMF curves of Figure 4 are not meant to be adjudged to represent the true halo IMF, but are merely included as a comparison, indicating that any form of Population III-style "pre-enrichment", if it even exists, is almost certainly based upon something resembling this more conventional form, as opposed to Chabrier et al.'s.

While we have not shown it graphically, extending the timescale for star formation, by decreasing ν by a factor of ten, say, only increases an already problematic discrepancy between observation (i.e. [C,N/O]$\approx$ -0.5) and theory (i.e. [C,N/O]$\gtrsim +0.5$) by lengthening the [C,N/O]$\gtrsim +0.5$ phase by a factor of ~ 3 over that shown in Figures 4 and 5.

Finally, we have only been concerned with recovering the mean halo dwarf abundance [C,N/O]≈ -0.5; we should remind the reader that there is a fairly wide spread in abundance ratios at these low metallicities (i.e. [Fe/H]$\lesssim -1.5$), with [C/O] as low as -1.2 dex being encountered (recall, though, our first footnote). This is a factor of ~ 2 lower than *any* single model in Woosley & Weaver's (1995) grid; there is *no* possibility of accounting for this tail of the population with their models. The situation would become considerably worse if we were to adopt the Langer & Henkel (1995) Type II SNe yields, as they are consistently $\sim 5 \rightarrow 8\times$ greater in [C/O] than Woosley & Weaver (1995), for $m \gtrsim 20\,M_\odot$. Maeder's (1992) [C/O] is typically 50% greater than Woosley & Weaver's (1995), for $m \lesssim 40\,M_\odot$. All of the above may be pointing to some underlying deficiencies in the existing stellar models, or perhaps postulating pollution from very massive stars (i.e. $m \gtrsim 40 \rightarrow 100\,M_\odot$ – a mass regime to which Woosley & Weaver's (1995) grid does not apply) will be necessary.

---

[7] There is a class of dwarfs in the halo (De Kool & Green 1995) with C>>O; Dearborn et al. (1984) speculated that the prototype of these dwarf carbon stars might bear the nucleosynthetic imprint of Population III-like pollution. The origin of these stars is now, however, generally attributed to binary mass-transfer from an AGB primary (Green & Margon 1994).

2.5. Hiding the Pollution

2.5.1. Absorbing the Residue

The above constraint on the WD-enriched luminosity function could *possibly* be relaxed for a very rapid collapse variant of the classical Eggen, Lynden-Bell & Sandage (1962) halo formation model. If star formation in the halo is complete within $\lesssim$ 70 Myrs (see Figure 4), the C,N products of the WD-enriched luminosity function could simply fail to be incorporated into the halo population by virtue of the longer evolutionary timescales of intermediate mass stars. These C,N products are inevitable, of course, but if they are lost to the halo and incorporated into the disk ISM, they might be diluted away by the primordial composition of the proto-disk. Unfortunately, this "escape" clause would appear to have at least one major problem, independent of any abundance arguments.

If we were to arbitrarily halt star formation at ~ 70 Myrs, for the Chabrier et al. (1996) IMF model of Figure 4, one could argue that the abundance constraints (i.e. [C/O]$\lesssim$ +0.3 and [N/O]$\lesssim$ +0.7) were not violated excessively, and, as it turns out, that the mass of the halo tied up in remnants (primarily WDs, with total mass $\sim 2 \times 10^{11}$ M$_\odot$) was not inconsistent with the microlensing statistics. Where this scenario suffers is in the sheer mass of gas postulated to settle to the disk. Ignoring any non-baryonic component to the halo, the model of Figure 4 requires an initial gas mass of $\sim 10^{12}$ M$_\odot$, in order to build up this halo WD mass of $\sim 2 \times 10^{11}$ M$_\odot$, when star formation is assumed to halt at $t \approx 70$ Myrs.[8] The resultant halo stellar (i.e. non-WD) mass is $\sim 10^9$ M$_\odot$, in agreement with that observed (Freeman 1996); this still leaves $\sim 8 \times 10^{11}$ M$_\odot$ of gas to absorb! Bearing in mind that the present-day mass of the thin+thick disk is only $\sim 0.6 \times 10^{11}$ M$_\odot$, it should be readily apparent that such halo-to-disk gas "absorption" scenarios, at least of this magnitude, are not a viable option.

2.5.2. Banishing the Residue

Halo *outflows*, similar to those expected during the early evolution of ellipticals (e.g. Gibson 1996a,b, and references therein), would appear to be a viable alternative to the disk "incorporation" of Section 2.5.1. Fields et al. (1996) have recently presented just such an hypothesis. A detailed accounting of their work is beyond the scope of this paper, but we do wish to draw attention to two potential problems:

(i) Fields et al. adopt the instantaneous recycling approximation; by assuming that the ejecta from AGB stars is returned on the same timescale as that from Type II SNe, they overestimate the local gas mass available for heating (and outflow) from the nearby SNe. In reality, the timescales are an order of magnitude different, which means that the bulk of the AGB ejecta (which itself is the bulk of the gas being returned, for the IMF in question) never experiences the local SN heating, and it would seem unlikely that planetary nebulae ejection could provide the necessary energy (Van Buren 1985).

(ii) More importantly, Fields et al. adopt Maeder's (1992) yields, assuming a black hole cut-off of $m = 18$ M$_\odot$, thereby avoiding the enrichment from precursors above this level (for halo metallicities in this mass range, stellar winds prior to the core collapse do not enrich the ISM in heavy elements – Maeder 1992). The minimum predicted halo dwarf [C/O] can only be as low as the minimum individual contributing star's [C/O] yield. Because Fields et al. are restricted to Maeder's (1992) low metallicity $m = 9 \rightarrow 18$ M$_\odot$ models, which span [C/O]$\approx$ +1.3 $\rightarrow$ −0.2, the minimum [C/O] possible within their framework is $\sim$ −0.2. In reality, because their IMF puts far more weight on the 9 M$_\odot$-end, as opposed to the 18 M$_\odot$-end, they will inevitably predict extremely carbon-rich [C/O] ratios ($>>$ +0.5) for the halo. Fields et al. appear to have neglected the CNO-enrichment from AGB stars in their code, but we need only refer back to Figure 3 to see that rectifying this omission will not aid in lowering the predicted [C/O] values. The Fields et al. outflow model *may* provide a means for hiding the bulk of the halo gas (although see point (i) above), and it may indeed be consistent with the distribution of global metallicity "Z" in the halo, but it *must* be inconsistent with the [C,N/O]$\approx$ −0.5 constraint from the halo dwarfs, in much the same way that our models of Figure 4 and 5 were.

In conclusion, it is difficult to envision a simple scenario which would allow one to (i) create ($\sim 2 \rightarrow 5) \times 10^{11}$ M$_\odot$ of halo WDs (as favoured by Adams & Laughlin 1996, Chabrier et al. 1996, and Fields et al. 1996); (ii) do so on a very short timescale (to avoid the abundance ratio problems); and (iii) not produce

---

[8]Reducing the star formation efficiency ν by a factor of ten, say, does not help. The $t_{max} \approx 70$ Myrs was chosen to avoid overproducing C and N; this holds, roughly, regardless of the value of ν. Unfortunately, because of the factor of ten lower star formation rate, we end up with approximately a factor of ten lower mass tied up in WDs after ~ 70 Myrs.

more than a few times 10^{10} $M_\odot$ of C,N-enriched unincorporated ejecta – not to mention the residual unincorporated primordial composition halo gas – to avoid violating the Galactic disk mass-constraint. The combination of points (i) and (ii) always results in approximately an order-of-magnitude overproduction of "hidable" gas.[9]

3. Summary

As a guide to future studies of chemical evolution of the Galactic halo, we note that a WD-precursor dominated IMF leads to an inevitable pollution of the halo ISM, at the levels [C,N/O]$\approx$ +0.0 $\rightarrow$ +1.5, in timescales $t \lesssim 0.1$ Gyr. *If* we interpret this IMF as Population III-related, one can construct models which are in agreement with the present-day WD luminosity function and the microlensing statistics, as stressed by Chabrier et al. (1996), and indeed with the inferred present-day halo mass-to-light ratio, as noted in Section 2.2. On the other hand, reconciling the implied nucleosynthesis with the observed [C,N/O] abundance pattern in the Population II halo dwarfs appears untenable. Invoking the argument that the above scenario could be retained, provided the halo star formation timescale was exceedingly short ($\lesssim$ 70 Myrs) and that any subsequent C,N-enriched gas diffused to the disk, thereby avoiding being locked into any of the Population II halo dwarfs, fails on the grounds that the sheer mass of gas that would need "hiding" in the disk would be up to an order of magnitude more massive than the present-day disk itself. Scenarios whereby this enormous quantity of gas is simply ejected from the halo *may* be a possibility, although we draw attention to the fact that the most sophisticated of such models leads inevitably to the identical halo abundance discrepancies (i.e. [C,N/O]$\gtrsim$ +0.5) illustrated in our study.

---

[9]By process of elimination, if one were determined to retain the notion of a purely baryonic dark halo, one might be tempted to side with De Paolis et al. (1997, and references therein), and throw support behind cold molecular clouds as the "hiding" place for the bulk of the halo's dark matter.

REFERENCES

Adams, F.C. & Laughlin, G. 1996, ApJ, 468, 586

Alcock, C., et al. 1993, Nature, 365, 621

Alcock, C., et al. 1997, ApJ, in press

Arnett, D. 1996, Formation of the Galactic Halo, ed. H. Morrison & A. Sarajedini, ASP Conf. Series, 337

Chabrier, G., Segretain, L. & Méra, D. 1996, ApJ, in press

Charlot, S. & Silk, J. 1995, ApJ, 445, 124

Dearborn, D.S.P., Liebert, J., Aaronson, M., Dahn, C.C., Harrington, R., Mould, J. & Greenstein, J.L. 1986, ApJ, 300, 314

De Kool, M. & Green, P. 1995, ApJ, 449, 235

De Paolis, F., Ingrosso, G., Jetzer, Ph. & Roncadelli, M. 1997, Dark and Visible Matter in Galaxies and Cosmological Implications, ed. M. Persic & P. Salucci, ASP Conf. Series, in press

Eggen, O., Lynden-Bell, D. & Sandage, A. 1962, ApJ, 136, 748

Fields, B.D., Mathews, G.J. & Schramm, D.N. 1996, ApJ, in press

Freeman, K.C. 1996, Formation of the Galactic Halo, ed. H. Morrison & A. Sarajedini, ASP Conf. Series, 3

Gibson, B.K. 1996a, MNRAS, 278, 829

Gibson, B.K. 1996b, ApJ, 468, 167

Gratton, R. & Caretta, E. 1996, Formation of the Galactic Halo, ed. H. Morrison & A. Sarajedini, ASP Conf. Series, 371

Green, P. & Margon, B. 1994, ApJ, 423, 723

Greggio, L. & Renzini, A. 1983, A&A, 118, 217

Hegyi, D.J. & Olive, K.A. 1986, ApJ, 303, 56

Fujimoto, M.Y., Sugiyama, K., Iben, Jr., I. & Hollowell, D. 1995, ApJ, 444, 175

Langer, N. & Henkel, C. 1995, Space Sci. Rev., 74, 343

Larson, R.B. 1986, MNRAS, 218, 409

Maeder, A. 1992, A&A, 264, 105

Marigo, P., Bressan, A. & Chiosi, C. 1996, A&A, in press

Méra, D., Chabrier, G. & Schaeffer, R. 1996, Europhys. Lett., 33, 327

Renzini, A. & Voli, M. 1981, A&A, 94, 175

Ryu, D., Olive, K.A. & Silk, J. 1990, ApJ, 353, 81

Salpeter, E.E. 1955, ApJ, 121, 161

Schaller, G., Schaerer, D., Meynet, G. & Maeder, A. 1992, A&AS, 96, 269

Timmes, F.X., Woosley, S.E. & Weaver, T.A. 1995, ApJS, 98, 617

Tornambè, A. 1989, MNRAS, 239, 771

Turatto, M., Cappellaro, E. & Benetti, S. 1994, AJ, 108, 202

Van Buren, D. 1985, ApJ, 294, 567

van den Hoek, L.B. & Groenewegen, M.A.T. 1996, A&A, in press

Woosley, S.E. & Weaver, T.A. 1995, ApJS, 101, 181